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Small bodies of the Solar System

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Discoveries of comets that behave like asteroids and asteroids that behave like comets are making us reassess our view of Earth's smallest neighbours.

Scientists have a strong urge to place Mother Nature's objects into neat boxes. For most of the past half century, the comets and asteroids of the Solar System did seem to belong in two separate populations — each within their own box. The rules were that comets, with a wide range of orbits, were solid, dirty iceballs originating in the so-called Oort cloud at the edge of the Solar System. Asteroids were defined as bits of rock confined mostly to a region between Mars and Jupiter and travelling roughly in the same plane and in the same direction as the planets about the Sun (Fig. 1). From time to time over the past 50 years, objects were found that did not really belong in either box, but they were only considered as occasional exceptions to the rules. Within the past few years, however, Mother Nature has kicked over the boxes entirely, spilling the contents and demanding that scientists recognize crossover objects — asteroids that behave like comets, and comets that behave like asteroids. As a result, the line between comets and asteroids is no longer clearly drawn.

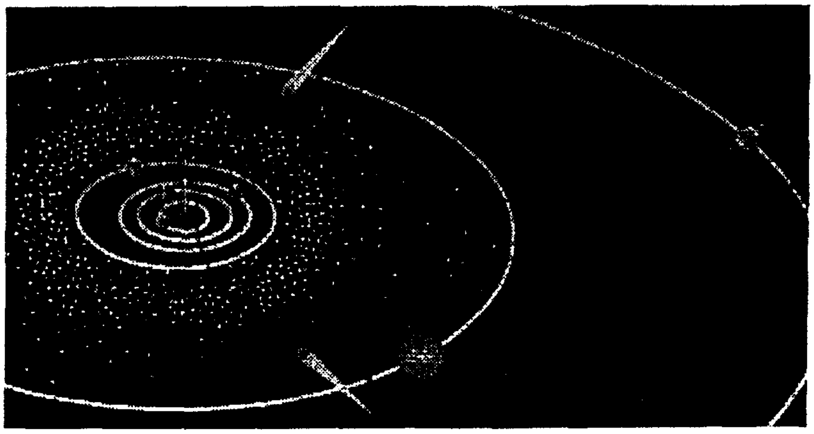


Figure 1 **The usual view of comets and asteroids. The inner Solar System contains the Sun and the four terrestrial planets: Mercury, Venus, Earth and Mars. The lumps of rock that make up the main asteroid belt between Mars and Jupiter orbit the Sun in the same plane and the same direction as the planets. Most comets have highly elliptical orbits, which means they spend most of their time in the outer reaches of the Solar System with only brief passages close to the Sun.**

Crossover objects

The modern model for the nucleus of a comet began with Fred Whipple in 1950–51. Whipple's 'dirty iceball' model for a cometary nucleus proposed a solid body, a few kilometres across, that is made up of various ices (frozen water, methane, ammonia, carbon dioxide and hydrogen cyanide) in which dust is embedded[1,2]. This model can explain the impressive dust tails we associate with comets passing the Sun. Dust particles are liberated when the ices vaporize as the comet approaches the Sun, and they get blown away by solar radiation pressure, often forming impressive, gently curved dust tails.

As the comet ages, dust becomes strewn all the way around its orbit. So when the Earth intersects this stream of cometary debris, a meteor shower (or storm) is the result. Almost all well observed meteor showers are associated with known comets. This was a neat, easily understood picture of the cometary ageing process. But it was Whipple himself who pointed out in 1983 that the orbit of the Geminid meteor stream was very similar to that of a recently discovered asteroid (3200 Phaethon) rather than a comet. Asteroid 3200 Phaethon is in a rather eccentric, comet-like orbit, and it is generally accepted that this asteroid, and a handful of others that have associated meteor streams, are defunct comets that have lost the ability to emit gas and dust.

A few years earlier, in 1977, the asteroid Chiron had been discovered in an orbit that takes it from just inside the orbit of Saturn to just inside the orbit of Uranus (Fig. 2, overleaf). There are now a few dozen of these so-called Centaurs, asteroids whose orbits lie in the outer planetary region. Although initially labelled as an asteroid, by early 1988, when it was approaching its minimum distance from the Sun (its *perihelion*), Chiron began to act in a decidedly non-asteroidal and more comet-like way. First, it became abnormally bright; then in 1989 it developed a dust atmosphere; and by January 1990 cyanogen gas emission was detected spectroscopically[3–5]. Chiron was the first object to receive a double designation as both an asteroid and a comet. It is now known as the ninety-fifth periodic comet (95P) and the two-thousand-and-sixtieth numbered asteroid (2060). So we have 95P/Chiron = (2060) Chiron.

To date, three objects have been officially recognized as having split personalities and have received a dual designation. The second is asteroid 1979 VA, which was discovered in 1979 in an eccentric, comet-like orbit. It comes as close as the Earth to the Sun, so one would expect it to produce gas near its perihelion if it were an active comet. A look back through old Palomar Sky Survey plates showed that the orbit predicted for this asteroid was identical to that of a comet discovered by Wilson and Harrington in 1949 (ref. 6). So asteroid 1979 VA had been a comet 30 years earlier and is now known as 107P/Wilson–Harrington = (4015) Wilson–Harrington.

The third object to receive a dual designation is 133P/Elst–Pizarro = (7968) Elst–Pizarro. Its orbit is very similar to that of a main-belt asteroid circling the Sun between the orbits of Mars and Jupiter, but it displayed a temporary, comet-like dust tail in 1996 (ref. 7).

Crossed paths

In the 1950s Jan Oort argued that comets with long orbital periods (millions of years) must spend most of their time in a vast spherical cloud surrounding the planetary system. There is no direct observational evidence for this so-called Oort cloud, but it is thought to extend out to about 100,000 times the Earth's distance from the Sun, or 100,000 astronomical units (AU). Later work on the origin of the long-period comets established that they formed in the colder region between the orbits of Jupiter and Neptune as the leftover bits and pieces from the formation of the Solar System. Once formed, many of these comets suffered close gravitational encounters with the major planets and were thrown either out of the

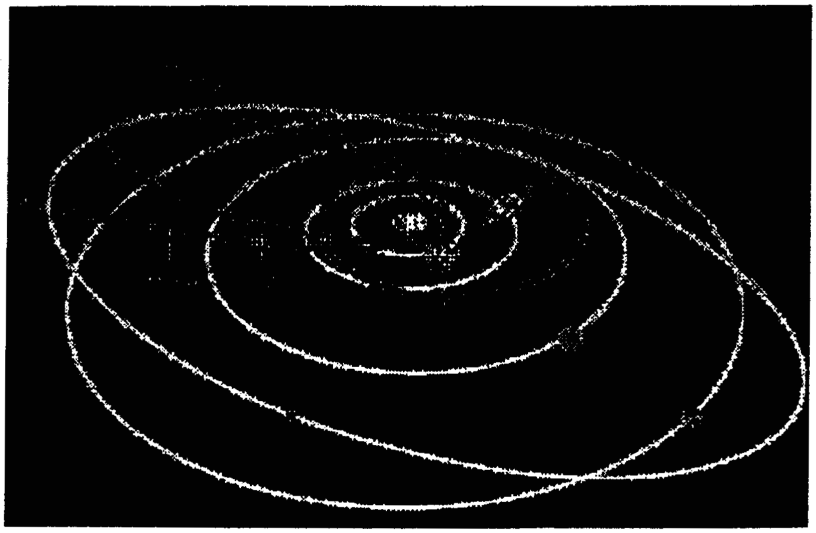


Figure 2 **Crossover objects in the outer Solar System. There are several asteroids (such as Chiron) whose orbits take them outside the main asteroid belt, into the outer Solar System. Chiron has an orbital period of 40 years, and has been seen to emit gas and dust like a comet. Other asteroids, such as 1996 PW (orbital period, 5,900 years) and 1997 MD10 (orbital period, 140 years), have very eccentric orbits, more like those of comets than asteroids.**

Solar System altogether or into the distant Oort cloud.

Upon reaching the Oort cloud, some bodies are thrown back into the planetary system by the gravitational perturbations of individual passing stars, the Galactic disk of stars, or giant molecular clouds of gas and dust. Coming from the roughly spherical Oort cloud, these long-period comets enter the inner Solar System with random prograde (same direction as planets) or retrograde (opposite direction to planets) orbits. This is unlike the short-period comets (periods less than 200 years), which have come under the gravitational influence of Jupiter, and usually orbit closer to the main plane of the Solar System in a prograde direction.

Most of the objects in the Oort cloud are probably comets that formed in the outer Solar System. But up to 3% of the current population could be asteroids that formed just inside Jupiter's orbit and then were pushed out, by way of gravitational interactions with Jupiter, to the very edge of the Solar System. The peculiar asteroid 1996 PW could be one of these objects (Fig. 2). It shows no comet-like activity and yet it has a very eccentric orbit and an orbital period of about 5,900 years, indicating that it is likely to have evolved back into the inner Solar System from the Oort cloud[8].

In addition, there are several other asteroidal objects in highly eccentric orbits — once considered the hallmark of comets. These include (3200) Phaethon with an orbital period of 1.4 years, 1997 MD10 with an orbital period of 140 years, and the recently discovered 1999 LE31 and 1999 LD31 with orbital periods of 23 and 120 years, respectively. The latter two objects are the first objects in the Solar System to be designated as asteroids with retrograde orbits. As mentioned earlier, object Elst–Pizarro has been given a dual comet and asteroid designation because it has shown cometary activity even though its nearly circular orbit is very similar to those asteroids in the main belt between the orbits of Mars and Jupiter.

We now have comets in asteroid-like orbits and asteroids in comet-like orbits. Both comets and asteroids can evolve from the Oort cloud into highly inclined, even retrograde, orbits about the Sun, so orbital behaviour is no better than physical behaviour for telling them apart. Our attempts to sort comets and asteroids into separate boxes have failed and astronomers should now consider these objects as members of a highly diverse family — the small bodies of the Solar System.

New family values

The blurring of the boundaries between comets and asteroids forces us to reassess our knowledge of the nature and origin of the small bodies of the Solar System. From time to time, some of these objects come too close to Earth for comfort, and the skies are being anxiously scanned for asteroids on a collision course with Earth. If we do find a threatening object then we need to understand its structure and composition, because plans to deflect a loose, fragmented structure out of our way would be entirely different from those to deflect a solid rock.

Astronomers are also interested in the structure of comets and asteroids because they represent some of the least processed material in the Solar System. As the leftover bits and pieces from early planetary formation, they offer clues to the primitive composition and conditions of the early Solar System. Spacecraft missions are key to understanding what is inside these objects, and future generations may actually benefit from these explorations. Interplanetary colonists will need to exploit the mineral, metal and water supplies of comets and asteroids, and mission planners will need to know which objects are the richest in natural resources and the easiest to mine.

It is possible that the ultimate answers to all these questions will not be found until the small bodies of the Solar System are explored more closely by spacecraft (Box 1). Nonetheless the loss of our standard picture of comets and asteroids is already providing a more diverse spectrum of possible structures — from porous balls of ice to solid rocks and slabs of iron.

Comets in transition

If all comets were solid, dirty balls of water ice, then their bulk densities would be about 1 $g\,cm^{-3}$. But it seems that some comets have rather crumbly, low-density structures that are made from several bits held together by little more than their own self-gravity. This conclusion arose because some comets were observed to break up as a result of tidal forces from either the Sun or Jupiter, and more than two dozen others have split apart for no obvious reason at all.

The most dramatic example of a tidally split comet was the disintegration of comet Shoemaker–Levy 9 into more than two dozen fragments when the comet passed close to Jupiter in July 1992 (Fig. 3). This was before it crashed into the surface of the giant planet two years later. Some contemporary press accounts reported that "the mighty tidal forces of Jupiter tore the comet to pieces", but the reality was rather less impressive. The tidal acceleration on the comet was no more than a wimpy 3 $mm\,s^{-2}$ or 0.0003 *g*. If you could have held a piece of comet Shoemaker–Levy 9 in your hand, it would have easily broken apart with only modest pressure. If we assume roughly equal sizes for the six comets that have split as a result of tidal forces from Jupiter or the Sun, then comet Shoemaker–Levy 9 suffered the greatest tidal disruptive force. It seems likely that the other five comets were at least as fragile and probably more so.

A comet made up of discrete chunks and held together by little more than self-gravity is best described by the 'rubble pile' model[9]. A rubble pile has almost no internal strength, very high porosity and correspondingly low bulk density. This model could explain how a comet like Shoemaker–Levy 9 can break up under very modest external forces. It could also explain why some comets, such as comet Biela in the 1850s, can break apart before disintegrating completely into a stream of meteoric particles with no remaining nucleus. Possibly the most fragile comets are created by millions of years of mutual collisions in the outer planetary system, where the nuclei are first broken apart and then re-accrete as loosely bound rubble piles[10]. Or, near the end of their active lifetimes, comets may lose the ices that cement together the separate pieces.

Comets that have already gone from active to quiescent (for example, Wilson–Harrington) suggest that some bodies do become defunct and join the ranks of the asteroids. Comet Encke, with its stable orbit within the orbit of Jupiter, is generally considered to be an active comet in transition to an asteroidal object. Comet 15P/Finlay may also be a low-activity transition object. It is the only active comet with an orbit suitably close to that of the Earth's that does not generate meteor showers, suggesting that it produces very little dust[11]. Low-density extinct comets can probably explain a significant fraction of the near-Earth asteroid population, so we cannot assume that all objects that threaten Earth will have the same composition or structure.

STScI/NASA

Figure 3 **Fragments of Comet Shoemaker–Levy 9. This short-period comet was in orbit around Jupiter and split into pieces when it got too close to the giant planet in July 1992. This image was taken by the Hubble Space Telescope in March 1994, four months before the comet dived into the atmosphere of Jupiter.**

Down to Earth

Asteroids have been classified according to the light reflected from their surfaces — their optical spectra. Although no two spectra are exactly alike, most asteroids fall into one of two groups, the C-type and S-type. C-type asteroids have low reflectance (albedo) and may contain mixtures of hydrated silicates, carbon and organic compounds. S-type asteroids have higher albedos and can contain pyroxene (silicates containing magnesium, iron and calcium), olivine (magnesium and iron silicates), and nickel–iron metal.

The darker, C-type asteroids are most common in the outer part of the main asteroid belt, whereas S-type asteroids are mostly found in the inner asteroid belt. The less common M-type asteroids contain mixtures of nickel–iron metal and magnesium or iron silicates. C-type asteroids are thought to be the most primitive because they have not been chemically differentiated, whereas S-type asteroids may have experienced internal or external heating that has separated them into different layers of material (similar to the Earth's separation into a core, mantle and crust). The metals found in some S- and M-type asteroids can be explained by melting processes similar to those seen in volcanic rocks on Earth.

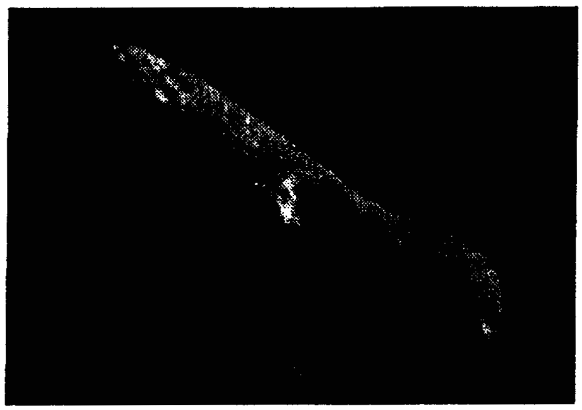
Meteorites are asteroid collision fragments that have fallen to Earth, and as such are thought to hold clues regarding the early history of asteroids. Because most asteroid fragments are rocky, they can survive the passage through the Earth's atmosphere,

Box 1 Love at first sight

On Valentine's day (14 February) 2000, the Near-Earth Asteroid Rendezvous (NEAR) spacecraft was successfully placed in orbit about the asteroid Eros — named for the Greek god of love. This successful rendezvous took place after the NEAR spacecraft had already made an en route fly-by of the C-type asteroid Mathilde in June 1997 and a fly-by of Eros itself in December 1998. This mosaic of four images was taken on 14 February 2000 at a distance of about 320 km from Eros. The view looks down on the north polar region of Eros. Currently, the orbiting NEAR spacecraft can only image the sunlit northern hemisphere: images of the remaining Eros landscape will not be possible until the southern hemisphere becomes sunlit in June 2000.

The large crater in this image is 6 km across, and cradles a boulder about 100 m in size. Eros is an S-type asteroid, which is heavily cratered over most of its surface, suggesting that it is relatively old. Images like this one are used to determine the shape of Eros and hence its volume. The mass of the asteroid has been determined by tracking the spacecraft as it slowly orbits Eros. By dividing the asteroid's mass by its volume, a preliminary estimate of 2.6 g cm^{-3} has been determined for the asteroid's bulk density — about the density of the Earth's crust. Although it is too early to draw definite conclusions, the asteroid's density coupled with some layered structures seen in the Eros images imply that Eros is not as porous as the asteroid Mathilde, observed by NEAR in 1997.

As well as the imaging camera used to take this picture, the NEAR spacecraft carries a full suite of scientific instruments, including an infrared spectrometer to identify various minerals, a lidar altimeter for determining the details of the asteroid's shape, a magnetometer for characterizing the asteroid's magnetic field, and an X-ray and gamma-ray spectrometer to determine its chemical composition. As the NEAR spacecraft moves to lower and lower orbits about Eros, these measurements will be used to improve our knowledge of the physical make-up and structure of this object and to identify what type of meteorite might be produced by an S-type asteroid like Eros.



JHU/APL

Although only designed to operate at an altitude of 50 km or less, the lidar began working successfully at its first opportunity on 29 February 2000 at a distance of 290 km from Eros. The X-ray spectrometer has also been able to deliver useful information earlier than anticipated thanks to three solar flares that occurred on 22 and 23 March 2000. Intense solar X-rays from these flare events caused certain chemical elements on the surface of Eros to fluoresce with characteristic energies, allowing the detection of magnesium, aluminum, silicon, calcium and iron. The NEAR spacecraft will remain in orbit about Eros for a year, making detailed studies of its surface morphology, shape and magnetic field, as well as its mineralogical and chemical composition. **D. Y.**

NSSDC/JHU/APL

Figure 4 **Close up to asteroids. a, The spacecraft NEAR flew by the C-type asteroid Mathilde (length 60 km) in 1997. Mathilde has at least five craters on its surface that are larger than 20 kilometres in diameter. Because its density is only 1.3 g cm^{-3}, it is likely to be a very porous asteroid. b, The S-type asteroid Ida (length 56 km) and its moon Dactyl (~1.5 km) were imaged by the Galileo spacecraft in 1993 on its way to Jupiter. Knowing Dactyl's orbit allowed scientists to estimate Ida's mass and density (~2.6 g cm^{-3}).**

whereas debris from comet streams nearly always burns up in the atmosphere, sometimes producing spectacular meteor showers in the sky but leaving little evidence on the surface of the Earth. The most common meteorite is the ordinary chondrite, which is composed mostly of rocky silicates, and so has not experienced the chemical differentiation associated with melting. These are thought to be some of the most primitive rocks in the Solar System, although their parent asteroid type is not clear.

On 22 March 1998, an ordinary chondrite was seen to fall to Earth by seven boys in Monahans, Texas. Within 48 hours, this meteorite was being examined at the Johnson Space Center in Houston, Texas[12]. Laboratory analysis of the Monahans meteorite detected salt crystals embedded with water in the form of brine, and the salt crystals were dated to the very beginning of the Solar System, some 4.6 billion years ago. Early in its lifetime, there must have been liquid water on the parent asteroid of this meteorite. Unless this water came from a collision with a salt-bearing icy comet, the parent asteroid itself must have had flowing water within its interior structure. Far from being the dry rocky bodies they were once thought to be, it would seem that some asteroids, along with comets, might be significant sources of water.

Asteroids in space

Of the two C-type asteroids for which we have reliable density information — 253 Mathilde and 45 Eugenia — both have bulk densities (about 1.3 g cm^{-3}) just higher than water[13–15]. If these objects were a bit less dense, they would float. Close-up images of Mathilde taken by the NEAR spacecraft in 1997 (Fig. 4a) suggest that the unusually large impact craters on its surface may have been created by compression of the surface during a collision, rather than by excavation of material[16]. In fact, Mathilde may have merged with some of the objects that hit it — increasing rather than reducing its mass. This means that its bulk density could once have been even less than it is now.

Mathilde and Eugenia must have very porous structures (greater than 50%) if they have the same composition as meteorites found on Earth. Meteorites that are thought to be collision fragments from C-type asteroids have bulk densities about twice that of their parent asteroids. There is growing evidence that at least some asteroids have interior structures closely resembling rubble piles.

The NEAR spacecraft orbited an S-type asteroid (433 Eros) earlier this year, and the asteroid's bulk density was found to be 2.6 g cm^{-3} (Box 1). In 1993 the Galileo spacecraft imaged the S-type asteroid 243 Ida and its moon (Fig. 4b). The bulk densities calculated for both S-type asteroids — Eros and Ida — are about twice that of the C-type asteroids Mathilde and Eugenia[17–19], so S-type asteroids may be more solid than their C-type cousins.

Radar observations of the M-type asteroid 16 Psyche suggest that it is likely to be metallic[20]. Moreover, the abundance of solid iron–nickel meteorites found on Earth suggests that there must be several solid metallic asteroids in near-Earth space to supply these bits of iron. Other asteroids are spinning at such a rate that they must be solid rock[21]. For example, the 30-metre-diameter asteroid (1998 KY26) must have considerable internal strength because it rotates in the very short time of only 10.7 minutes (ref. 22), which is more than fast enough to break up a rubble pile. From physical evidence alone, it appears that the structures of asteroids run from fluffball ex-comets to rubble piles, solid rocks and slabs of solid iron.

Friend or foe?

Because comets and asteroids are the relatively unchanged bits and pieces left over from the formation of the Solar System, studying their structures and compositions provides clues to the mixture and conditions of the pre-planetary accretion disk from which the planetary bodies agglomerated some 4.6 billion years ago. Knowledge of their structures and compositions is also important in the unlikely event that one is found on an Earth-threatening trajectory. The best technology to deflect an object out of harm's way would depend critically on the nature of the object itself. More than one deflection strategy is needed to deal with fluffball ex-comets and slabs of solid iron.

Those small bodies that most closely approach Earth are also the most accessible for the future mining of their natural resources. In terms of landing a spacecraft on their surface, there are several asteroids that are more accessible than the Moon itself. If the inner Solar System is to be colonized within the coming years, the necessary materials for interplanetary structures, such as habitats, are likely to come from the wealth of minerals and metals provided by asteroids[23]. Because it costs several thousand dollars per pound to launch materials into Earth's orbit and beyond, it would be far more cost effective to build these structures from nearby natural resources found in space. The water supplies necessary for sustaining life and for providing hydrogen and oxygen for rocket fuels are also likely to come from comets. Asteroids and comets may one day become the workshops, or fuelling stations and watering holes, of future planetary exploration. ■

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Related sites

- **http://near.jhuapl.edu/**
- **http://near.jhuapl.edu/Mathilde/**
- **http://nssdc.gsfc.nasa.gov/planetary/chiron.html**
- **http://www.jpl.nasa.gov/sl9/**